Simulation of Heat Exchanger under Fouled Conditions

by

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CERTIFICATION OF APPROVAL

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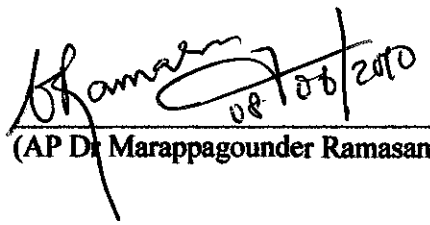

(AP Dr Marappagounder Ramasamy)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

KHAIRUL FAHMI BIN MOHAMAD NOR

ABSTRACT

This paper introduces brief ideas for "Simulation of heat exchanger under fouled conditions" research which includes its background study, objectives, literature review, research methodology, results, discussion, recommendation and conclusion. In the initial part of this paper, the fouling characteristic is discussed based on the literature review. Fouling in heat exchanger is one of the major challenge need to be encounter by all industrial practitioner in plant especially in oil refinery plant. This problem had caused plant to increased their capital and operational cost because of inaccurate prediction of accumulation of fouling in the heat exchanger. This paper also quotes and discussed some literature and research of a few scholars about the fouling model characteristic and performance. In the methodology, the steps taken throughout the project is discussed briefly. The modelling of crude preheat train and simulation done is explained. Next, result and discussion for this project is analyzed. In the last part, a few recommendations are proposed to enhance the project before the project is concluded.

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CHAPTER 1
INTRODUCTION

1.1 Background of study

Fouling, a term originally used in the oil industry, is defined as the accumulation of deposits on heat exchanger surfaces, which obstructs the transfer of heat and increases the resistance to fluid flow (Epstein, 1983; Taborek et al., 1972). The growth of these deposits causes the thermal and hydrodynamic performance of heat transfer equipment to decline with time. Fouling is generally classified into five categories according to the principle process: crystallization, particulate, chemical reaction, corrosion and biological fouling (Hong Yu, 2007). A mail survey covering 3000 heat exchangers from New Zealand showed that more than 90% of heat exchangers suffered from fouling problems. In any industrial plant, it is important not only to be able to measure the build up of unwanted deposits, but also to do it in the simplest and most economically possible way (Muller-Steinhagen, 2000).

This project will be focusing on monitoring heat transfer characteristic of the fouled heat exchanger in the oil refinery plant, where the high number of heat exchanger units and the variability of the crude oil feed composition and properties happened. In this case, the flow rates and the quality of the fluids flowing through the heat exchanger do not usually correspond to the design conditions because they keep changing with time. So monitoring of the day to day thermal efficiency cannot be compared to the efficiency of the design calculation. Fouling is closely related with the thermal efficiency of heat exchanger. Some companies even evaluate the fouling from the value of thermal efficiency. Low thermal efficiency indicates high fouling occurred in the heat exchanger (L.F Melo, A. Sousa Braga et al., 1996).

Common ways to monitor the performance of the heat exchanger are done by monitoring the pressure drop and temperature difference of inlet and outlet condition. However, there is a lot of discrepancy of using this method. One of the current ways in monitoring the thermal efficiency of fouled heat exchanger will be briefly discussed in the literature review. Several heat exchangers in an oil refinery were successfully monitored using this method (L. F Melo, A. Sousa Braga et al., 1997).

1.2 Problem Statement

Fouling of heat exchanger can cause a lot of problems to the plant especially in refinery plant. Enormous costs are associated with the heat exchanger fouling but only limited research has been done to determine accurately the economic penalties due to fouling and to attribute these costs to the various aspects of heat exchanger design and operation. Fouling related cost is simplified in the table below (Bohnet, 1987; Bolt, 1995; Muller-Steinhagen, 1999).

Table 1.1: Cost related to fouling in plant

No	Cost	Description
1.	Increased capital investment	More materials for the construction of heat transfer equipment
2.	Additional operational cost	Higher energy consumption due to thermal efficiencies and pressure drop
3.	Higher maintenance cost	Due to the local corrosion of tubes and additional cleaning systems
4.	Loss of production	Due to deteriorating product quality and inability to meet operational demand and unforced shutdown for clean up
5.	Cost of remedial action	Such as additives to reduce fouling and chemicals to clean fouled surfaces.

It is estimated that the total cost of heat exchanger fouling accounts for about 0.25% Gross Domestic Product (GDP) of industrialized countries during the 1980s and 1990s. (Muller-Stainhagen, et al., 2005). Therefore, it is important to monitor the fouling and to study the effect of fouling to the heat exchanger performance in order to avoid the cost-related to this problem.

1.3 Objectives

The objective of this project is to study the effect of fouling on heat transfer characteristic of the heat exchanger in the crude preheat train through simulation. The heat exchanger data will be taken from Petronas Penapisan (Melaka) Sdn. Bhd (PPMSB). The simulation used for this project is Petro-SIM. From the simulation, the fouling resistance is manipulated to study the heat exchanger performance in term of heat exchanger duty, log mean temperature difference (LMTD) and crude outlet temperature of the heat exchanger. The effect of fouling will be studied on individual and also all heat exchangers in the crude preheat train.

1.4 Scope of Study

The scope of study for this project consists of a few tasks and research that need to be conducted. The first stage of study is to know the theoretical background of the heat exchanger design, heat transfer characteristic and fouling characteristic. Understanding on this theoretical knowledge will assist the student to work on the problem during the simulation later. Besides that, the student also needs to do the research on the current method done by industrial practitioner in order to monitor the fouling performance of the heat exchanger to provide better understanding on the fouling characteristic. On top of that, the student needs to familiarize with the simulation software to be used that is Petro-SIM. The successful of this simulation will depend on how the student manages to integrate the data of heat exchanger to produce best analysis of heat exchanger characteristics.

CHAPTER 2
LITERATURE REVIEW

This section will briefly discuss about the theoretical background of fouling and the design operation of heat exchanger. Then, the current method of evaluating fouling in the heat exchanger will be discussed which include the fundamental concept and calculation to represent fouling thickness and fouling thermal resistance.

2.1 Types of fouling

As mentioned earlier, there are five types of fouling involves in heat exchanger. The first one is crystallization fouling. This involves the crystallization of dissolved species from solution onto the heat exchanger surface. This happened when process conditions lead to supersaturation of the dissolved inorganic salts at the heat transfer interface. The next type of fouling is particulate fouling. This fouling is defined as the deposition of particles suspended in liquid onto heat transfer surfaces. Suspended particles may include pollutants/species always present in the feed stream or product of the chemical reactions occurring within the fluid (Bolt, 1997).

The third fouling is chemical reaction fouling which included deposits that are formed at heat transfer surfaces as a result of chemical reaction within the process fluid. The forth fouling is corrosion fouling. In this case, the heat exchanger material reacts with the fluid to form corrosion products on the heat transfer surfaces. This classification only restricted to in situ corrosion processes. The last type of fouling is biological fouling which refers to the development and deposition of organic films consisting of microorganisms and the attachment and growth of macro-organism (Bolt, 1997).

2.2 Sequence of fouling

The overall fouling process can be explained by referring to the Figure 2.1 below. The figure shows an idealised graph of the rate of growth of a deposit on a surface which consists of three regions. In region A, the process of adhesion is initiated. The induction period may take a long time, perhaps of the order of several weeks or may be of the order of minutes or even seconds. Region B represents the steady growth of the deposit on the surface. During this region, there is competition between deposition and removal. Factors that may influence the deposition or adhesion of foulant are van der Waals forces, electrostatic forces and external force fields at wall while the removal may occur as a result of spallation, erosion or dissolution (Bolt, 1997).

The rate of deposition gradually decreases while the rate of removal deposit gradually increases. Finally the rate of removal and the rate of deposition may become equal so that a plateau steady state is reached. This is where the last region, Region C occurred (Bolt, 1997).

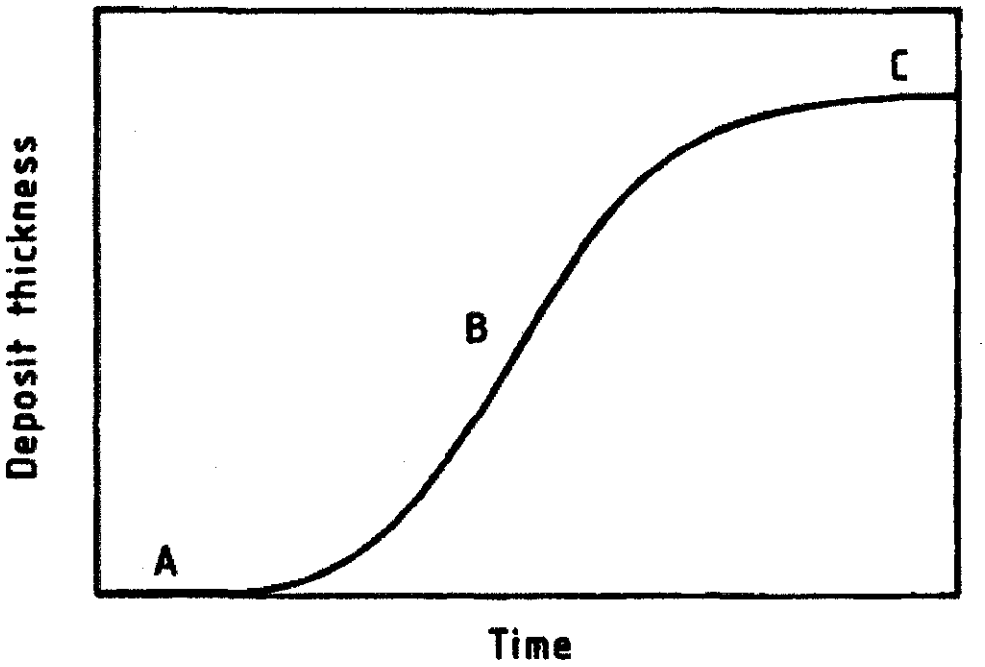

Figure 2.1: The change in deposit thickness with time

2.3 Conditions that Influence Fouling

There are a few conditions that could influence fouling in the heat exchanger. These conditions can be divided as operating parameters, fluid properties and heat exchanger design parameters (Garrett-Price et al., 1985).

2.3.1 Operating Parameters

Surface temperature, bulk temperature and fluid velocity are among the most important parameters that affect the rate of fouling. For a process involving chemical reactions, higher surface temperature tends to increase fouling rate due to an increased reaction rate. Variation in the fluid viscosity between the heat transfer surface and bulk fluid may affect transport of fouling species due to temperature gradient across the wall boundary layer (Bolt, 1997).

Fluid velocity is a critical factor with respect to both deposition and removal processes. Higher velocities will enhance the mass transfer of fouling species from the bulk liquid to the heat transfer surface and the intensity of the removal force, but tend to reduce the efficiency of surface adhesion for foulant (Bolt, 1997; Pinheiro, 1986; Yiantsios and Karabelas, 2003).

2.3.2 Fluid Properties

The nature of the fluid and the species dissolved or entrained in the fluid are known to affect fouling processes. For example, water quality in cooling water systems has a significant impact on potential fouling mechanisms which may involve crystallization of inversely solubility salts, deposition of particulate matters, corrosion and biological fouling (Knudsen, 1981).

2.3.3 Heat Exchanger Parameters

Heat exchanger parameters such as surface materials, surface structure and type and geometry of exchanger could also affect the fouling potential. For instance, rough surfaces are known to promote fouling by providing additional nucleation sites for deposition (Knudsen and Roy, 1982; Suitor et al., 1977). Copper and brass alloy surfaces generally foul more than stainless steel surface from the added effect of corrosion (Suiter,et al., 1977) and higher surface energy (Tyson, 1975; Mantel, et al.,1995). Plate heat exchangers also tend to have lower fouling rates than tubular exchangers due to the turbulence generated by the corrugations on the plate (Knudsen and Roy, 1982).

2.4 Fouling Resistance

For steady state conditions, the heat flux, q" across a clean surface is given as:

$$q" = U_C \Delta T_m \tag{2.1}$$

Where: q" = heat flux

U_c = overall heat transfer coefficient for clean condition

ΔT_m = log mean temperature difference between hot and cold fluids

The log mean temperature can be calculated using the equation below:

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{2.2}$$

Where: ΔT_1 = temperature difference between hot fluid

ΔT_2 = temperature difference between cold fluid

The relation between the overall heat transfer coefficients with the resistance is defined as:

$$\frac{1}{U_c} = R_{\overline{TC}} = \frac{1}{h_h} + R_{\overline{W}} + \frac{A_h}{A_C h_C} \tag{2.3}$$

Where: R_{TC} = total resistance to heat flow

A_c = cold fluid side heat transfer area

$\frac{1}{h_h}$ = film resistance of the hot fluid

$\frac{A_h}{A_C h_C}$ = film resistance of the cold fluid

R_W = resistance to heat flow of the metal wall

The heat flux across a fouled surface is given as:

$$q = U_D \Delta T_m \tag{2.4}$$

Where:

$$\frac{1}{U_D} = R_{TF} = \frac{1}{h_h} + R_W + R_f + \frac{1}{h_C} \tag{2.5}$$

where R_f is the resistance of fouling to heat transfer. Thus, the so called fouling resistance or fouling factor can be redefined as:

$$R_f = \frac{1}{U_D} - \frac{1}{U_C} \tag{2.6}$$

and

$$q'' = \frac{1}{\frac{1}{U_C} + R_f}(T_w - T_b) \tag{2.7}$$

Where: T_W = wall temperature

T_b = bulk temperature

If the wall temperature T_w is to be kept constant, heat flux q" decreases with the increasing R_f, thus results in a lower temperature of cold fluid. Alternatively, if the heat reflux q" remains constant (the deposit/fluid interface temperature remains the same as the clean wall temperature value), T_w must be increased with the increasing R_f (Knudsen and Roy, 1982).

If the total available heat transfer area A is taken into account, the rate of heat transfer q is expressed as:

$$q = U_D A \Delta T_m \tag{2.8}$$

In the design of heat exchanger, it is necessary to determine the area, A required for the heat transfer. So the equation need to be rearrange to estimate the required heat transfer area under fouling conditions and the impact of fouling on the heat exchanger design.

$$A = \frac{q}{U_D \Delta T_m} = \left(\frac{1}{\frac{1}{U_C}} + R_f\right)\frac{q}{\Delta T_m} \tag{2.9}$$

From the equation, the choice of the individual fouling resistance for the calculation of U_D will have a great influence on the size of the heat exchanger and hence the capital cost.

2.5 Effect of fouling on velocity of fluid

The rate of build up of deposit on a surface could be defined by the simple concept of the difference between the rate of deposition and removal. In mathematical terms;

$$\frac{dm}{dt} = \emptyset_D - \emptyset_R \tag{2.10}$$

Where: m = mass of deposit

$\emptyset_D$ = deposit mass flow rate per unit area

$\emptyset_R$ = removal mass flow rate per unit area

The increased heat transfer resistance of the foulant layer can have two further effects. If the deposit thickness is appreciable, then the area for fluid flow and the cross sectional area of a tube is reduced. For the same volume flow, the fluid velocity will increase and for identical conditions, the Reynold number will increase.

For the clean tube diameter, d_1 and the volumetric flow rate is V, the original velocity is given by;

$$u_1 = V\frac{4}{\pi d_1^2} \tag{2.11}$$

If due to fouling process, d_1 is reduced to $d_1/2$, thus the new velocity u_2 for the same mass flow rate is a fourth time the original velocity or given by:

$$u_2 = V\frac{4\,x\,4}{\pi d_1^2} = \frac{16\,V}{\pi d_1^2}$$

The Reynolds number is defined as:

$$Re = \frac{4V\rho}{\pi d_1 \eta} \tag{2.12}$$

Where: p = density of fluid

η = viscosity of fluid

The corresponding Reynolds number will be doubled due to the presence of deposit if d_1 is reduced to $d_1/2$ as shown in the equation below.

$$Re = \frac{4V\rho}{\pi\frac{d_1}{2}\eta} = \frac{8V\rho}{\pi d_1 \eta}$$

2.6 A Simple General Model of Fouling

The simplest model of represent the build up of deposit with time but ignoring the induction period would have the form:

$$x_f = \frac{dx}{dt}.t \tag{2.13}$$

Where x_f is the thickness of deposit at time t. If the induction time is t_i, then the equation become:

$$x_f = \frac{dx_f}{dt}.(t - t_i)$$

In term of fouling resistance, the above equation will be:

$$R_f = \frac{dR_f}{dt}.(t = t_i) \qquad (2.14)$$

The difficulty in using this model is that without experimental work, dx/dt and dR/dt is unknown. Thus one of the simplest models to explain the fouling process was defined by Kern and Seaton [1959]. This model is essentially a mathematical interpretation of the asymptotic fouling curve as shown in the Figure 1.

$$R_{ft} = R_{f\infty}(1 - e^{\beta t}) \qquad (2.15)$$

Where:
- R_{ft} = fouling thermal resistance at time t
- $R_{f\infty}$ = fouling thermal resistance at time t
- β = constant dependant on system properties

The actual value of the constants will depend upon the type of fouling and the operating conditions. Some detailed experiment need to be conducted to predict these values. As the research will be time consuming, Kern and Seaton [1959] proposed a mathematical restatement of the initial equation with tubular flow in mind of the form:

$$\frac{dx_f}{dt} = K_1 c' M - K_2 \tau x_{ft} \qquad (2.16)$$

Where:
- $K_1 c' M$ = the rate of deposition term similar to first order reaction
- $K_2 \tau x_{ft}$ = the rate of removal term
- K_1 and K_2 = constant
- c' = foulant concentration
- M = mass flow rate
- x_t = the foulant layer thickness at time t

τ = the shearing stress = fpu^2

f = friction factor

Assume c' and M are constant because of steady state flow, and x_f the thickness is very much less than the tube diameter for deposition in a tube, the integration of Equation 2.16:

$$x_f = \frac{K_1 c' M}{K_2 \tau}(1 - e^{-K_2 \tau t}) \qquad (2.17)$$

This equation is similar to Equation 2.15 in form with $\frac{K_1 c' M}{K_2 \tau}$ a constant for a given set of operating equations and equivalent to $R_{f\infty}$. $K_2\tau$ is also a constant and equivalent to β. Kern and Seaton [1959] also developed the theory further using the Blasius relationship, to make allowance for the change in flow area caused by the deposition process.

$$f = \frac{\tau}{pu^2} = K_f Re^{-0.25} \qquad (2.18)$$

Where, K_f is the Blasius constant and $\Delta p = 4\frac{\tau l}{d_i p 2g}$

Where d_i is the inside diameter of the tube and l is the length of tube in the direction of flow.

Under this condition, for turbulent flow:

$$x_{f\infty} = \frac{2K_1 c'}{K_2}\left[\frac{\pi^2 g p l^4 M^3}{K_f (\Delta p_\infty)^4}\right] \qquad (2.19)$$

Where Δp_∞ is the pressure drop at the asymptotic value of the foulant thickness. $\frac{K_1 c'}{K_2}$ characterises the fouling qualities of the fluid and generally will remain constant. If the practical data be available for one set of condition, the thickness of the asymptotic value of the fouling thickness at a different set of conditions can be obtained by this equation from the ratio:

$$\frac{x_{f\infty 1}}{x_{f\infty 2}} = \frac{\left[\frac{l^4M^3}{\Delta p_\infty{}^4}\right]_2^{1/5}}{\left[\frac{l^4M^3}{\Delta p_\infty{}^4}\right]_1^{1/5}} = \left[\frac{l_2}{l_1}\right]^{0.8}\left[\frac{\Delta p_{\infty 1}}{\Delta p_{\infty 2}}\right]^{0.8}\left[\frac{M_2}{M_1}\right]^{0.8} \qquad (2.20)$$

The subscript 1 and 2 refer to the two set of conditions. In general it can be assumed that the mechanism of removal will be similar in most situations since it will depend upon the conditions at the fluid/foulant interface although the cohesive strength of the foulant layer will be different in different example (Kern and Seaton, 1959). The driving force for asymptotic fouling for any mechanism is suggested as the difference between the asymptotic fouling resistance and the fouling resistance at time t (Konak, 1973). Assuming a power law function;

$$\frac{dR_f}{dt} = K(R_{f\infty} - R_{ft})^n \qquad (2.21)$$

where K and n is a constant. The final equation becomes (Kern and Seaton, 1959);

$$\left[1 - \frac{R_{ft}}{R_{f\infty}}\right]^{1-n} - 1 = KR_{f\infty}{}^{n-1}t \quad for\, n \neq 1$$

$$-ln\left[1 - \frac{R_{ft}}{R_{f\infty}}\right] = Kt \quad for\, n = 1$$

As most of the constant in this general model is unspecified and need further research and experimental work, another model is used in the industry in order to monitor the performance of heat exchanger fouling.

2.7 Fouling Resistance Calculation

In the earlier part of literature review, several modeling and representation of fouling are discussed. However in real situation, slightly difference approach is used in order to calculate the fouling resistance. Most of the formulas used are referred from the Heat Transfer (Principles and Applications) book written by Binay K. Dutta and Introduction of Heat Exchanger written by Incropera, DeWitt et al.

Fouling resistance, R_f in the heat exchanger can be calculated using the equation below:

$$R_f = \frac{1}{U_A} - \frac{1}{U_C} \tag{2.22}$$

where :

U_A = Overall heat transfer coefficient at actual condition ($W/m^{2o}C$)

U_C = Overall heat transfer coefficient at clean condition ($W/m^{2o}C$)

R_f = Fouling resistance ($m^{2o}C/W$)

The calculation part is divided into a few sections to avoid any confusion.

2.7.1 Overall Heat Transfer Coefficient (Actual Condition)

The value of U_A can be calculated from the current process and design data provided by the plant. Usually all four temperatures of inlet and outlet for cold and hot stream are available from the temperature and flow indicator at plant. Generally, overall heat transfer coefficient can be calculated from the heat transfer rate equation below:

$$Q = UA\Delta T \tag{2.23}$$

Considering various design of heat exchanger and fouling happened in the heat exchanger, value of U_A is defined as:

$$U_A = \frac{Q}{Ao\Delta T_{CM}} \tag{2.24}$$

where :

Q = Heat transfer rate (MW)

A_o = Effective surface area (m^2)

ΔT_{CM} = Corrected mean temperature driving force (°C)

Value of Ao is available in the design data. The heat transfer rate, Q can be calculated using the equation below where value of mass flowrate (m), specific heat capacity (Cp) is also available in the design data.

$$Q = mCp\Delta T \tag{2.25}$$

The value of Q can be calculated depending on the mass flowrate of cold or hot stream of the heat exchanger that is available. If the cold stream flowrate is used, the value of Cp and ΔT of cold stream must be used too. The value of ΔT_{CM} can be calculated using the equation below.

$$\Delta T_{CM} = F_T \Delta T_M \tag{2.26}$$

where :

F_T = LMTD Correction factor

ΔT_M = Log mean temperature difference (°C)

Log mean temperature difference in defined as:

$$\Delta T_M = \frac{(T_{H,in} - T_{C,out}) - (T_{H,out} - T_{C,in})}{ln\left(\frac{T_{H,in} - T_{C,out}}{T_{H,out} - T_{C,in}}\right)} \tag{2.27}$$

where :

$T_{H,in}$ = Hot stream inlet temperature (°C)

$T_{H,out}$ = Hot stream outlet temperature (°C)

$T_{C,in}$ = Cold stream inlet temperature (°C)

$T_{C,out}$ = Cold stream outlet temperature (°C)

The LMTD correction factor, F_T is defined as:

$$F_T = \frac{\frac{\sqrt{R^2+1}}{R-1} ln\left(\frac{1-\tau_C}{1-R\tau_C}\right)}{ln\left[\frac{\left(\frac{2}{\tau_C}\right)-1-R+\sqrt{R^2+1}}{\left(\frac{2}{\tau_C}\right)-1-R-\sqrt{R^2+1}}\right]} \tag{2.28}$$

where:

Capacity ratio, $R = \frac{T_{H,in} - T_{H,out}}{T_{C,out} - T_{C,in}}$

Temperature ratio, $\tau_C = \frac{T_{C,out} - T_{C,in}}{T_{H,in} - T_{C,in}}$

The value of F_T and ΔT_M will be used in equation 2.26 to get the value of ΔT_{CM}. Then value of U_A is calculated using equation 2.24 from the value of Q, Ao and ΔT_{CM} calculated earlier.

2.7.2 Overall Heat Transfer Coefficient (Clean Condition)

The value of Uc can be calculated based on the outside (Uc,o) or inside (Uc,i) surface area. For a given heat exchanger, inside refer to tube side while outside refer to shell side of the heat exchanger. For the case based on outside surface area,

$$U_{C,o} = \frac{1}{\frac{d_o}{d_i h_i} + \frac{d_o \ln(\frac{d_o}{d_i})}{k_w} + \frac{1}{h_o}} \tag{2.29}$$

For calculation based on inside surface area,

$$U_{C,i} = \frac{1}{\frac{d_i}{d_o h_o} + \frac{d_i \ln(\frac{d_o}{d_i})}{k_w} + \frac{1}{h_i}} \tag{2.30}$$

Considered the case based on the outside surface area, where:

d_i = Tube inside diameter (m)

d_o = Tube outside diameter (m)

k_w = Thermal conductivity of tube wall (W/mK)

h_i = Tube side heat transfer coefficient (W/m^2K)

h_o = Shell side heat transfer coefficient (W/m^2K)

The values of d_i, d_o and k_w is available in the design data of the heat exchanger. The value of h_i and h_o can be calculated using the equation below:

For inside (tube side) heat transfer coefficient, hi is defined as:

$$h_i = \frac{Nuk}{d_i} \tag{2.31}$$

where:

Nu = Nusselt number

k = Thermal conductivity of product flow through tube (W/mK)

di = Inside tube diameter (m)

The calculation of Nusselt number depends on the fluid condition. There are a few models have been introduced as shown below:

Sieder-Tate equation modified by McAdams:

$$\bar{N}u = 0.027\,\bar{R}e_t^{0.8}\bar{P}r_t^{1/3}\left(\frac{\mu_t}{\mu_w}\right)^{0.14} \tag{2.32}$$

Colburn equation:

$$\bar{N}u = 0.023\,\bar{R}e_t^{0.8}\bar{P}r_t^{0.4}\left(\frac{\mu_t}{\mu_w}\right)^{0.14} \tag{2.33}$$

Dittus-Boelter equation:

$$Nu = 0.023\,Re_t^{0.8}Pr_t^{n} \tag{2.34}$$

where:

n = 0.3 (cooling) or 0.4 (heating)

Re_t = Reynolds number (tube)

Pr_t = Prandtl number (tube)

μ_t = Dynamic viscosity of product flow inside the tube (cP)

μ_w = Dynamic viscosity of product flow near the wall (cP)

The value of μ_w is available in the design data. The suitable equation to be used depends on the value of Re_t and Pr_t calculated previously. Reynolds number and Prandtl number can be calculated from the equations below:

$$Re_t = \frac{\rho u_m di}{\mu} \tag{2.35}$$

$$Pr_t = \frac{\mu C_p}{k} \tag{2.36}$$

where:

ρ = Density (kg/m^3)

u_m = Mean fluid velocity over tube cross section

d_i = Inside tube diameter (m)

μ = Dynamic viscosity (cP)

Cp = Heat capacity (J/kgK)

k = Thermal conductivity (W/mK)

For outside (shell side) heat transfer coefficient ho is defined as:

$$h_o = \frac{Nuk}{d_o} \tag{2.37}$$

where:

Nu = Nusselt number

k = Thermal conductivity of product flow through shell (W/mK)

do = Outside tube diameter (m)

Similar to the inside heat transfer coefficient, the calculation of Nusselt number for outside heat transfer coefficient also depends on the fluid condition. There are a few models have been introduced as shown below:

Hilpert equation:

$$Nu = CRe_s^{\ m} Pr_s^{\ 1/3} \tag{2.38}$$

Zukauskas equation:

$$Nu = CRe_s^{\ m} Pr_s^{n} \left(\frac{Pr_s}{Pr_w}\right)^{0.14} \tag{2.39}$$

where:

n	=	0.37 (Pr <10) or 0.36 (Pr>10)
Re_s	=	Reynolds number (shell)
Pr_s	=	Prandtl number (shell)
Pr_w	=	Prandtl number of product flow near the wall
C,m	=	Constant of equation (depends on value of Re_s)

The suitable equation to be used depends on the value of Re_s and Pr_s calculated previously. Reynolds number and Prandtl number can be calculated from the equations below:

$$Re_s = \frac{\rho V do}{\mu} \tag{2.40}$$

$$Pr_s = \frac{\mu C_p}{k} \tag{2.41}$$

where:

V	=	Mean fluid velocity through shell side
d_o	=	Outside tube diameter (m)

The value of product density (ρ), dynamic viscosity (μ), thermal conductivity (k) and heat capacity (Cp) for product flow in the tube side and shell side are extracted from the simulation Petro-SIM. Solving the value of hi and ho, the value of Uc can be calculated using the equation 2.29 or 2.30.

2.7.3 Overall Heat Transfer Coefficient (Fouled Condition)

From the value of U_C and U_A, fouling resistance, R_f is calculated using equation 2.22. The value of overall heat transfer coefficient of fouled condition, U_f can be calculated using the equation below.

$$U_f = \frac{1}{R_f} \tag{2.42}$$

2.7.4 Heat Transfer Effectiveness and Efficiency

Effectiveness of heat exchanger is also one of the important factors that are used to evaluate the performance of heat exchanger. The calculation of effectiveness only considers the temperature inlet and outlet of cold and hot stream. Effectiveness of heat exchanger, □ is defined as:

$$\eta = \frac{actual\ heat\ transfer}{maximum\ possible\ heat\ transfer} = \frac{Q}{Qmax} = \frac{T_{H,in} - T_{H,out}}{T_{H,in} - T_{C,in}} \qquad (2.43)$$

The more accurate way to evaluate the performance of heat exchanger is by calculating the value of efficiency. Efficiency of heat exchanger can be determined from the equation below:

$$\text{Efficiency} = \frac{U_A}{U_C} \qquad (2.44)$$

2.7.5 Fouling Thickness

The amount of material deposited or the fouling thickness, x_f is related to the fouling resistance. The fouling thickness is defined as:

$$x_f = k_f R_f \qquad (2.45)$$

where k_f is the thermal conductivity of the foulant.

CHAPTER 3
METHODOLOGY

The simulation of heat exchanger under fouled conditions is a new approach in determining the heat transfer performance in the heat exchanger network (HEN). This project will involve a few steps which consist of;

3.1 Literature Review

Journals and articles regarding the heat exchanger design, heat transfer characteristic and fouling characteristic were compiled and analyzed to give concrete understanding about the project.

3.2 Project Activities

3.2.1 Familiarization of Petro-SIM software

This project will used one of the current simulation software used in PETRONAS companies that is Petro-SIM. Petro-SIM is rigorous simulation software that will allow the user to model from a specific unit to an entire plant. Familiarization of using this software will be the successful key to produce the good simulation in order to represent the fouling in the heat exchanger.

3.2.2 Simulation to be performed in Petro-SIM

The steps to be performed in the Petro-SIM are shown in the process flow below:

1. Heat Exchanger Modelling in Petro-SIM

The heat exchanger model will be set up from the design data. As mentioned in Chapter 1 earlier, the data will be taken from PP(M)SB. The set up will be done for one of the heat exchanger (E 09) to study the effect of fouling to the heat transfer characteristic of individual heat exchanger.

2. Simulation of Heat Exchanger Model in Petro-SIM

The value of fouling resistance in the heat exchanger E 09 will be manipulate to study the effect of fouling resistance on heat exchanger duty, overall heat transfer coefficient and LMTD value.

3. Heat Exchanger Network Modelling and Simulation

The simulation setup is done to all of the heat exchanger in the crude preheat train. The fouling resistance for heat exchanger E 11 will be manipulated to analyze the cascading effect of fouling to the heat transfer characteristic in the heat exchanger network.

4. Analysis of simulation results

The results will be represented in the graph and analyzed. Interpretation of the results will be done and further enhancement on the simulation model will be discussed later.

3.2.3 Spreadsheet Calculation

From the simulation, the data from Petro-SIM will be transfer to the Microsoft Excel to produce spreadsheet calculation. The calculation formula is based on the literature review part. The heat exchanger performance is evaluated based on many factors such as heat exchanger duty, LMTD and crude outlet temperature. The results are tabulated for a single heat exchanger and also the heat exchanger network.

3.3 Key milestone for FYP II

Table 3.1: Suggested key milestone of the project

	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Preheat Train Heat Exchanger Setup														
2	Data Gathering and Analysis														
3	Submission of Progress Report 1														
4	Data Gathering and Analysis														
5	Spreadsheet Calculation														
6	Result Interpretation and Improvement														
7	Submission of Progress Report 2														
8	Finalization of Result and Discussion														
9	Seminar														
10	Poster Exhibition														
11	Submission of Dessertation Report														
12	Oral Presentation														
13	Submission of Project Dissertation														

3.4 Software / Tools Required

There are two softwares that will be used in this project as shown in the table below.

Table 3.2: List of software used in the project

No.	Software	Licensor	Brief Description
1.	Petro-SIM	PETRONAS	Petro-SIM is a rigorous simulation software package that will allow the user to model from a specific unit to an entire plant. Process variables and unit operation topology can be easily manipulate and fully customized for the simulation.
2.	Microsoft Excel	MICROSOFT	Microsoft Excel is one of the simplest spreadsheet data used for calculation of many variables and data. This simulation can be linked with the Petro-SIM and easily used to produce results in graphical form.

CHAPTER 4
SIMULATION SETUP

The simulation set-up is done in the Petro-SIM software. This software is chosen because it is the common simulation used in PETRONAS. The steps in the simulation set-up are divided into three parts as shown below:

1) General Simulation Environment Setup

2) Preheat Train Setup
   i) Refinery feed
   ii) Stream setup
   iii) Heat exchanger setup

Brief steps and data used in the simulation are explained below.

4.1 General Simulation Environment Setup

In this part, student must specify the master component list, fluid package, hypotheticals and oil manager information. The component used for this simulation is refinery default. In Petro-SIM, for refinery simulation, the default components are already been develop in the software. This is one of the advantages of using this software compare to others.

For the fluid package, the Peng-Robinson (PR) equation of state is used. This is because it is the most widely used cubic equation of state in the refinery and gas processing industries for the prediction of vapour-liquid equilibrium for system containing non-polar components (Chorng H. Twu, 1998).

After the selection of fluid package, the hypothetical and oil manager setup is specified to represent the component in the preheat train. In this part, product hypothetical, refinery assay, product assay and product cut is specify based on the KBC datasheet. For refinery assay, all of the crude used in PP(M)SB is already been setup. The student just need to create the product assay and product cut based on the KBC crude assay database. The example of the datasheet is attached in the Appendices.

4.2 Preheat Train Setup

After the general simulation setup, student will enter the simulation environment to proceed with the preheat train setup. There are three main parts in the preheat train setup which are refinery feed, stream setup and heat exchangers setup.

4.2.1 Refinery Feed

First of all, the refinery feed need to be set up. This is to represent the crude oil feed to the preheat train. There are 23 different types of crude used in the refinery operation based on KBC databases. Mole fraction of the crude used is set based on the crude blend done on the daily operation. The data need to be specify in the refinery feed are source of crude, mole fraction of crude, mass flowrate, temperature and pressure of the crude.

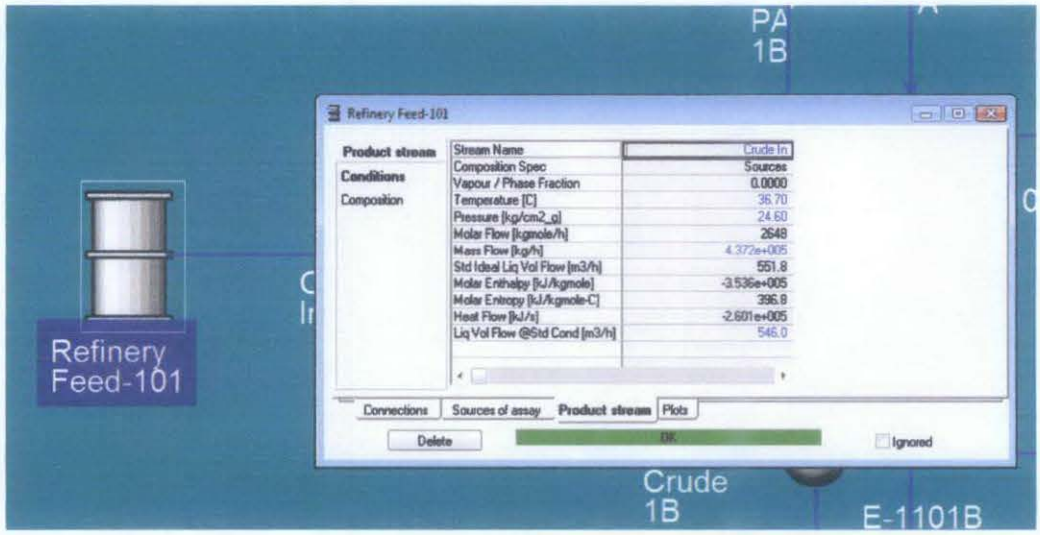

Figure 4.1: Refinery feed specification

4.2.2 Stream Setup

For the stream setup, there a few data need to be specified which are temperature, pressure, mass flowrate and component of the stream. The data is taken from the heat exchanger datasheet. The component of the crude and product flow in the heat exchanger is chose based on the assay created in the part 1. The figure below is the example of stream specification for crude stream.

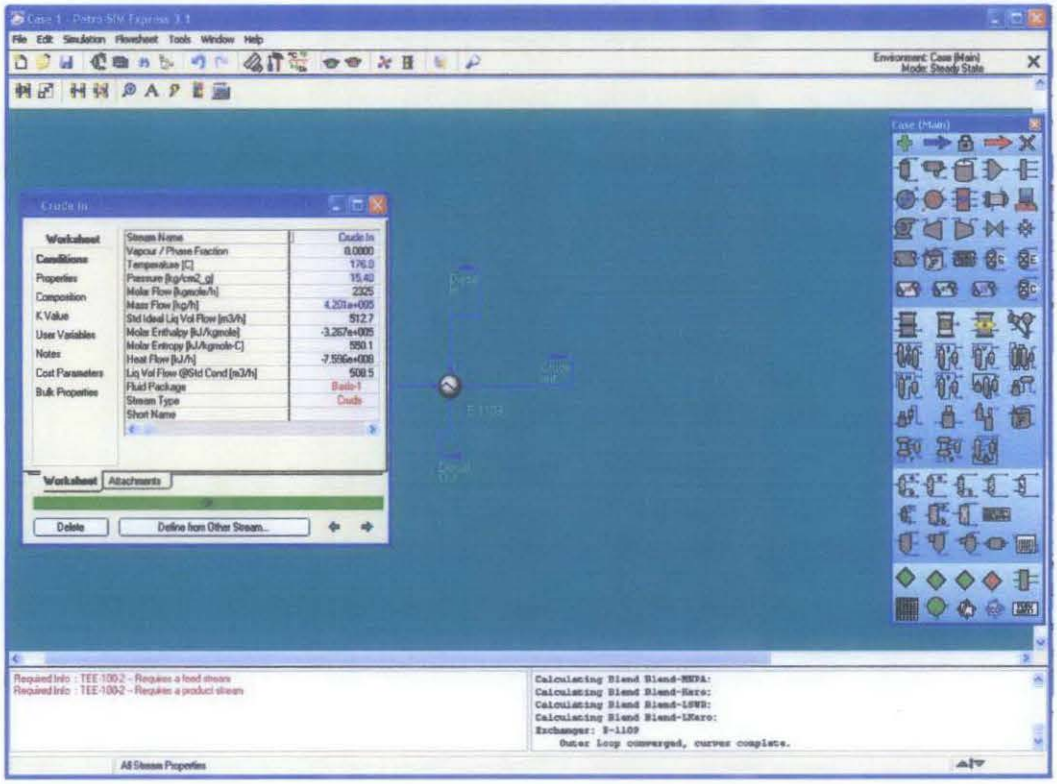

Figure 4.2: Crude stream specification

4.2.3 Heat Exchanger Setup

The heat exchanger used for the simulation is shell and tube heat exchanger. In is important to know the principle of the heat exchanger such as which fluid should be flow through tube and shell side. In refinery operation, the principle is the product that has high possibility of fouling will be flowing through the tube side. This is because the cleaning of tube side is easier to be conducted compare to shell side.

The data for heat exchanger setup is available in the heat exchanger datasheet. The example of heat exchanger datasheet is attached in the Appendices. The important data to be specified for heat exchanger in the simulation are shown in the table below. The others data need to be specified are highlighted in the datasheet.

Table 4.1: Example of specification for heat exchanger setup

Data	Specification
TEMA type	AES
Shell DP (kPa)	8.826
Tube DP (kPa)	17.65
Shell heat transfer coefficient ($W/^0Cm^2$)	941
Shell heat transfer coefficient ($W/^0Cm^2$)	1769
Shell Fouling ($^0Cm^2/W$)	0.00035
Shell diameter (mm)	1200
No of tubes per shell	1498
Tube OD (mm)	19.05
Tube ID (mm)	14.83
Tube length (m)	6.096
Tube Fouling ($^0Cm^2/W$)	0.00062
Thermal Conductivity (W/mK)	60

The stream and heat exchanger is arranged based on the process flowsheet of preheat train in PP(M)SB. The resulted simulation model is shown in the figure below:

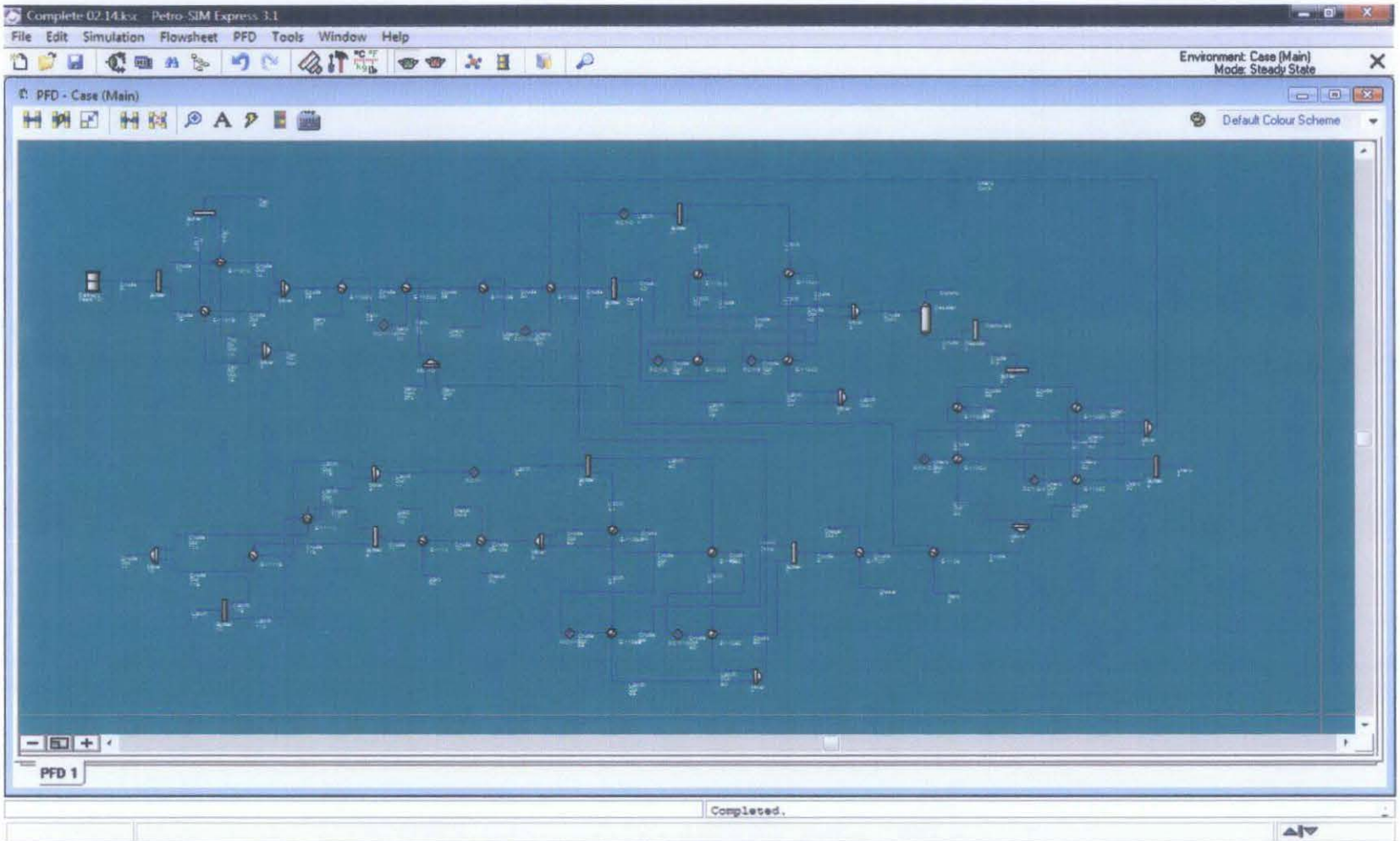

Figure 4.3: Simulation model for crude preheat train

CHAPTER 5
RESULTS AND DISCUSSION

The results for this simulation are divided into two sections; the study for individual heat exchanger (E 09) and the crude preheat train.

5.1 Results and Analysis of Fouling in Individual Heat Exchanger

The analysis of the heat exchanger is done for heat exchanger E 09 in Petro-SIM. The data used in the simulation is based on the design data. In real situation, the data such as temperature outlet, heat duty and others data keep changing with time. One of the factors that affect the heat exchanger performance is fouling. In heat exchanger E 09, the product flows in the shell side is diesel and the crude oil flows in the tube side. As crude has higher tendency to produce fouling compare to diesel, for the fouling resistance, R_f analysis, the value of R_f for tube side is manipulated. Others data are set to be constant. The R_f value of tube side is change to know the effect of R_f to the heat exchanger performance. The heat exchanger performance is evaluated based on the value of heat duty, temperature log mean difference and overall heat transfer coefficient. The result is shown in the table below:

Table 5.1: Results of heat exchanger performance analysis

Rf ($^\circ Cm^2/W$)	Tc inlet $^\circ C$	Tc, out $^\circ C$	Tprod, in $^\circ C$	Tprod, out $^\circ C$	LMTD $^\circ C$	Qc,in kW	Qc,out kW	Heat Duty, Q kW	U_A $W/^\circ Cm^2$
0.00010	176	198	265	195	37.73	-211011	-204294	6717	236.89
0.00016	176	198	265	195	38.11	-211011	-204332	6679	229.85
0.00031	176	197	265	196	39.18	-211011	-204441	6570	212.09
0.00047	176	197	265	197	40.26	-211011	-204554	6456	196.88
0.00062	176	197	265	199	41.34	-211011	-204669	6341	183.70
0.00078	176	196	265	200	42.42	-211011	-204786	6225	172.18
0.00093	176	196	265	201	43.48	-211011	-204902	6109	162.01
0.00109	176	196	265	202	44.51	-211011	-205017	5993	152.98
0.00124	176	195	265	204	45.52	-211011	-205132	5879	144.91

The value of Rf from the design data is 0.00062 $^{o}Cm^{2}/W$. This value is set to be the medium value. The lowest value is chose by manipulate the simulation so that it is converge and from the manipulation, value of 0.0001 $^{o}Cm^{2}/W$ is taken as the lowest fouling value for the tube side of the heat exchanger. The largest value for tube fouling is set to be double the value of the design fouling. The intermediate value is chose and for each Rf value, the required data such as crude and product outlet temperature, heat flow and overall heat transfer coefficient is taken from the simulation and tabulated as shown in the table above. For better analysis, the result is represented in the graph below:

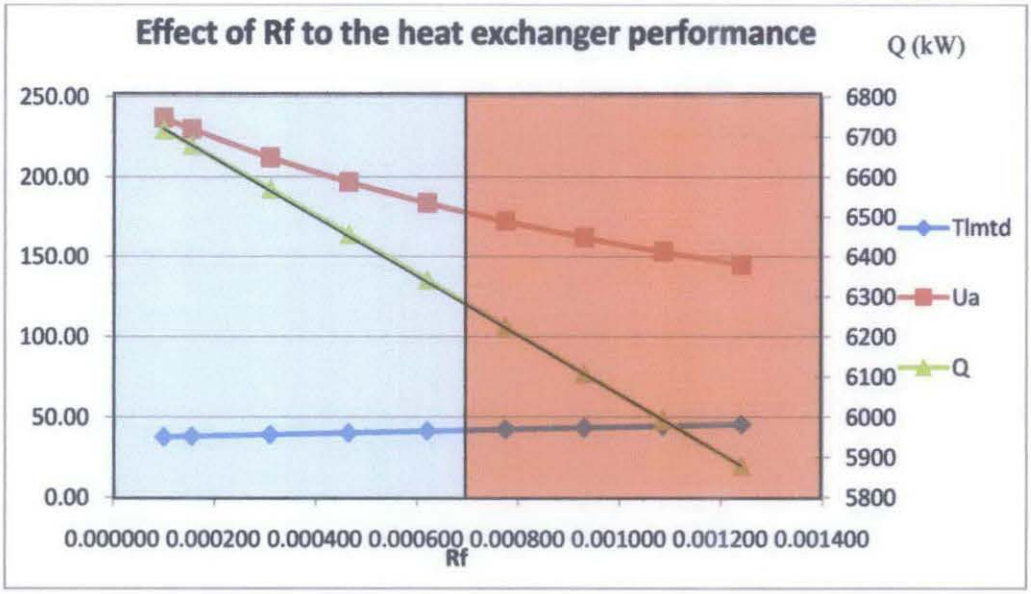

Figure 5.1: Effect of fouling resistance on the heat exchanger performance

The graph is analyzed as two different parts. The first part (red region) is the part where the design value of Rf is increased to become double of design value and the second part is where the Rf value is reduced to the minimum value. From the graph, in the first part, when Rf increase, log mean temperature (LMTD) increase while heat duty,Q and overall heat transfer coefficient ,U_A is decrease. For the second parts, when Rf decrease, log mean temperature (LMTD) decrease while heat duty,Q and overall heat transfer coefficient ,U_A is increase. These results can be explained using the equation 2.22, 2.24 and 2.27 in literature review section.

5.1.1 Effect of fouling resistance to the log mean temperature difference (LMTD)

Log mean temperature difference is calculated using the formula below.

$$\Delta LMTD = \frac{(T_{H,in}-T_{C,out})-(T_{H,out}-T_{C,in})}{ln\left(\frac{T_{H,in}-T_{C,out}}{T_{H,out}-T_{C,in}}\right)}$$

From the formula, the value of LMTD is highly dependent on difference of temperature between hot and cold stream. From Table 5.1, as Rf increases, the difference between the inlet and outlet value of both stream, crude and diesel is decreases. This is because as fouling resistance increase, the heat transfer from the product to the crude is reduced. So the outlet temperature of hot stream will be higher while the outlet temperature of the cold stream will be lower compare to the design value. Thus, as the value of Rf increases, the LMTD is also increases.

5.1.2 Effect of fouling resistance to the overall heat transfer coefficient

The relationship between fouling resistance and overall heat transfer coefficient, U_A is mentioned in the equation 2.22 below.

$$R_f = \frac{1}{U_A} - \frac{1}{U_C}$$

From the formula, the value of Rf is dependent on the value of U_A. The overall heat transfer coefficient for clean condition is constant. Rearrange the equation,

$$U_A = \frac{1}{R_f + \frac{1}{U_C}}$$

The value of U_A is inversely proportional to the value of R_f. Thus as R_f increases, U_A is decreases. From the definition, U_A is a measure of the overall ability of a series of conductive and convective barriers to transfer heat. Therefore, when fouling increases,

the ability of the tube wall to transfer heat from hot fluid to cold fluid is reduces. Therefore the value of U_A is decreases when the fouling resistance increases.

5.1.3 Effect of fouling resistance to the heat exchanger duty

The effect of fouling to the heat exchanger duty can be explained using equation 2.24. Rearrange the equation, the heat exchanger duty is defined as:

$$Q = U_A A o \Delta T_{CM}$$

From this equation, the value of Q is dependent on the value of U_A and LMTD. From the graph, the value of U_A decrease faster compare to the value of LMTD increasing. Thus the value of Q will be decreases when the Rf value increases. From this analysis, as the fouling resistance increases, the heat exchanger performance is decreases in term of LMTD, heat duty and U_A.

5.2 Results and Analysis for Crude Preheat Train Simulation

The study of fouling effect to the heat transfer characteristic of preheat train will be focusing on the heat exchanger duty, log mean temperature difference and overall heat transfer coefficient. The temperature and flowrate of crude and products in the simulation is taken based on the daily operation data. The chosen date for this simulation study is based on 1st November 2008 data. Listed below are the operation data based on 1st November 2008.

Table 5.2: Operation Data on 1st November 2008

Heat Exchanger	Shell side			Tube Side		
	Component	T,in (°C)	Flowrate (kg/h)	Component	T,in (°C)	Flowrate (kg/h)
E 01	Top P/A	148.2	488627	Crude	35.8	391470
E 02	Kerosene	178.43	104073	Crude	85.99	391470
E 03	Light Kero	158.90	162308	Crude	102.72	391470
E 04	Crude	108.35	391470	LSWR	190.12	84115
E 05	Light Kero	182.86	157023	Crude	117.39	436736
E 06	Kerosene	212.25	62052	Crude	129.16	436736
E 07	AGO	228.98	22263	Crude	134.42	436736
E 08	Crude	143.64	436736	LSWR	296.12	78025
E 09	Diesel P/A	287.06	51458	Crude	170.27	436736
E 10	AGO P/A	334.84	12403	Crude	180.73	436436
E 11	Crude	184.86	436736	LSWR	332.55	71885

The fouling resistance for all heat exchanger is set to the design value. So far, the fouling resistance in the tube side of heat exchanger E 11 is manipulated to see the cascading effect to the other heat exchanger performance. From the plant history, the previous maximum value of fouling happened in the heat exchanger is up to 0.01 $°Cm^2/W$. Thus, the manipulation of the fouling resistance value is done up to the maximum fouling value. The manipulation value of fouling resistance is shown in the table below:

Table 5.3: E 11 Fouling Resistance Manipulation Value

Fouling increment (%)	Fouling resistance value ($°Cm^2/W$)
Design Value	0.00044
20	0.000528
50	0.00066
100	0.00088
500	0.00264
1000	0.00484
2200	0.01000

At each value of fouling resistance, the value of inlet and outlet temperature for product and crude, heat exchanger duty and overall heat transfer coefficient is tabulated in the excel spreadsheet. The calculation is done to find the value of LMTD, heat duty and overall heat transfer coefficient, U_A. For the value of overall heat transfer coefficient, it is found out that there is no change to the value except for heat exchanger E 11. This is because the value of U_A is calculated based on the value of fouling resistance provided to the heat exchanger. So there will be no effect to the value of U_A. The results will emphasize on the percentage difference of the heat exchanger duty, LMTD and crude outlet temperature from the design value.

As the fouling resistance for E 11 is increases, there are two primary effects that happen to the CPT which are the outlet temperature of the product stream (LSWR) will be increase while the outlet temperature of the crude will be decreases. Thus, more heat will be transferred to the next heat exchanger by the LSWR products which in this case in heat exchanger E 08. The cascading effect of fouling in E 11 is analyzed further in section 5.2.1, 5.2.2 and 5.2.3.

5.2.1 Effect of fouling resistance to the percentage difference in log mean temperature difference, LMTD

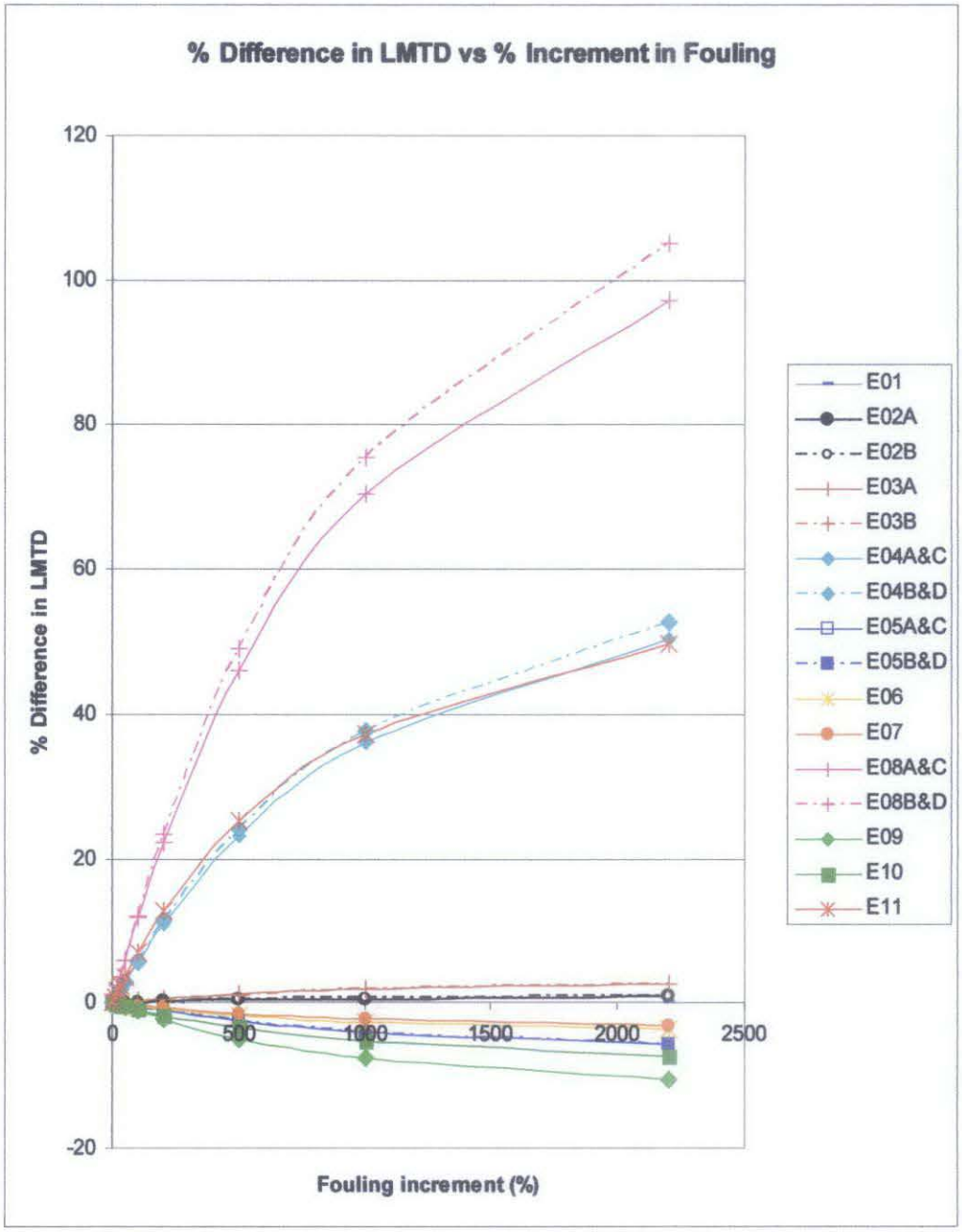

Figure 5.2: Effect of Fouling Increment on the value of LMTD

The graph shows the effect of LMTD when the value of fouling resistance for heat exchanger E 11 is increased. The results are further simplified in the table below:

Table 5.4: Effect of Fouling Increment on the LMTD

Effect to the value of LMTD	Heat exchanger	Maximum difference with the LMTD design value (°C)	
		Value difference	Percentage
Constant	E 01 A/B	0	0
Increase	E 08 A/C	52.958	97.189
	E 11 A/B	42.095	49.564
	E 08 B/D	35.682	104.994
	E 04 A/C	23.520	50.353
	E 04 B/D	17.15	52.716
	E 03 A	1.316	2.598
	E 03 B	1.264	2.712
	E 02 B	0.668	0.931
	E 02 A	0.526	0.963
Decrease	E 09	-8.228	-10.581
	E 10	-4.847	-7.289
	E 05A/C	-3.048	-5.635
	E 05B/D	-2.695	-5.634
	E 06	-2.100	-3.711
	E 07	-1.631	-3.270

The results above can be explained by referring to the process flow diagram (PFD) of the preheat train attached in the appendices. The value of LMTD for heat exchanger E 01 is constant because it is independent of other heat exchanger in the heat exchanger network. The value of LMTD for heat exchangers E 02, E 03, E 04, E 08 and E 11 are increases and the rest of heat exchangers are decreases.

The value of LMTD represents the temperature driving force for heat to be transfer. In this HEN model, the amount of heat to be transfer only depends on the inlet temperature of crude and product in each of the heat exchanger. The higher the temperature difference between inlet of product and crude, the higher the temperature driving force, thus value of LMTD will be higher.

The impact of fouling in heat exchanger E 11 must be analyzed from each heat exchanger to another individually. For example, in heat exchanger E 08, as mention earlier, there is increment in the inlet temperature of LSWR to the heat exchanger. So the difference between the inlet temperature of crude and LSWR will be higher. This is why the LMTD value for heat exchanger E 08 is increases.

For heat exchanger E 09, as more heat is transfer to the crude in E 08, so the outlet temperature of crude going to E 09 will be higher. The inlet temperature of the product stream (Diesel) is constant. Thus the inlet temperature difference between crude and product will be decrease and as a result, LMTD for E 09 will be decreases.

The change of the value LMTD affect the most on the heat exchanger that are closely related to the E 11 because there are higher temperature difference at those heat exchangers.

5.2.2 Effect of fouling resistance to the percentage difference of heat exchanger duty, Q

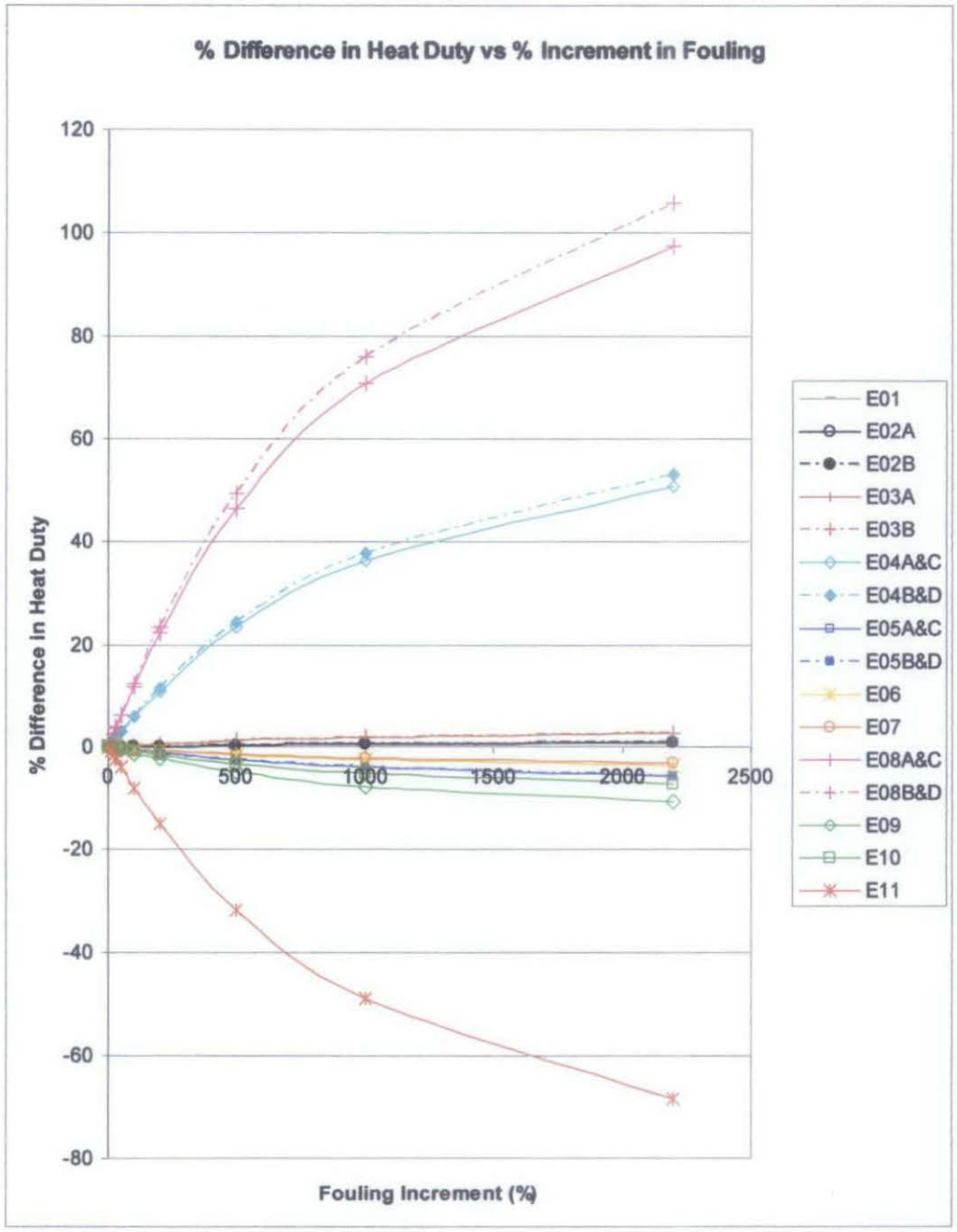

Figure 5.3: Effect of Fouling Increment on the Heat Exchanger Duty, Q

This graph shows the effect of fouling increment in E 11 to the heat exchanger duty, Q. Overall, the changing in heat exchanger duty value is more significant compare to the LMTD value. For simplicity, parts of the results are shown in the table below:

Table 5.5: Effect of Fouling Increment on the Heat Exchanger Duty,Q

Effect to the value of Tlmtd	Heat exchanger	Maximum difference with the heat duty design value (kW)	
		Value difference	Percentage
Constant	E 01 A/B	0	0
Increase	E 08 A/C	1072.12	97.46
	E 08 B/D	723.39	105.66
	E 09	396.19	10.52
	E 04 A/C	338.04	50.49
	E 04 B/D	246.56	52.91
	E 10	152.28	7.14
	E 05 A/C	86.02	5.57
	E 05 B/D	77.50	5.67
	E 06	62.35	3.56
	E 07	34.75	3.08
Decrease	E 11	-2836.48	-68.38
	E 03 A	-50.24	-2.65
	E 03 B	-46.24	-2.65
	E 02 A	-16.96	-1.00
	E 02 B	-13.10	-1.01

There are reduction in the heat duty value for heat exchangers E 02, E 03 and E 11. The reduction for E 11 is the most significant that is more than 2800kJ/h. The value of heat duty for E 01 is constant while the others heat exchangers are increase differently based on the relation with E 11.

Generally, the trend of the graph for heat duty is almost the same with the LMTD graph except for heat exchanger E 11. The trend is almost the same because base on heat duty formula, $Q=U_A A_o \Delta T_{LMTD}$, heat duty is directly proportional with the LMTD value. Thus, when value of LMTD increases, heat duty Q will also increases. For heat exchanger E 11, the heat duty is decrease because as fouling resistance increases, the value of U_A will be decreases. The reduction in U_A value is higher compare to the increment in LMTD value. Thus heat duty for the heat exchanger will be decreases.

From the data collected, the net heat duty for the entire HEN is also calculated. The net heat duty is referred to the total amount of heat transferred from the product stream to the crude stream in all heat exchanger in HEN. The result is shown in the table below:

Table 5.6: Difference in Net Heat Duty of entire HEN

Fouling increment (%)	Net heat duty (kW)	Difference of Net heat duty
Design	47201.28	-
20	47162.58	-38.6995
50	47099.87	-101.409
100	47004.87	-196.409
500	46396.71	-804.569
1000	45948.24	-1253.04
2200	45442.48	-1758.8

From this table, as the fouling increase, the net heat duty for entire HEN is decrease. This indicates that the plant will require additional energy to make up the energy lost due to fouling.

5.2.3 Effect of fouling resistance to the crude outlet temperature

The result for effect of fouling resistance to the crude outlet temperature is shown in the Figure 5.4 below. The graph shows that the value of crude outlet temperature is increase for all heat exchanger except for E 01 and E 11. For E 01, there is no change to the crude outlet temperature because the heat exchanger does not relate with the recycle of product stream. The value of crude outlet temperature is decrease in E 11 is because of the fouling resistance that is set in the simulation. As the fouling increase in the heat exchanger, the amount of heat to be transfer from product to crude will be decrease, thus the temperature of the crude stream will also decrease. The crude outlet temperature for heat exchangers are increase because fouling occurred at the last heat exchanger in HEN. Thus more heat exhange favored to happen in the initial part of the HEN.

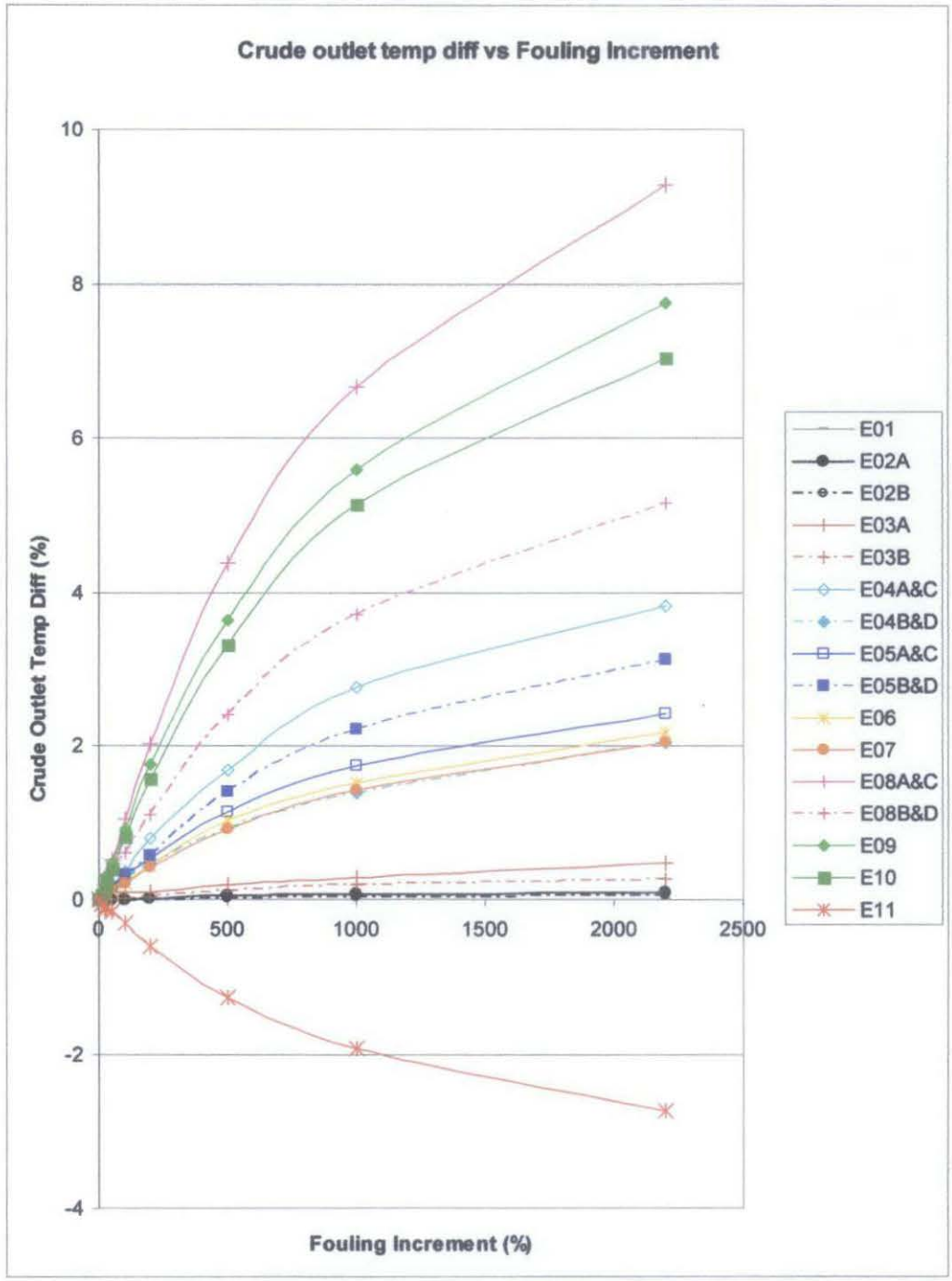

Figure 5.4: Effect of Fouling Increment on the Crude Outlet Temperature

CHAPTER 6
RECOMMENDATION AND CONCLUSION

From the analysis of results in chapter 5, it is conclude that the fouling resistance is inversely proportional to the heat exchanger performance. As the fouling resistance increases, the performance of the heat exchanger in term of heat duty, overall heat transfer coefficient and outlet temperature are changing differently based on the relations of the heat exchanger to the fouled heat exchanger. As the fouling accumulates, the poor heat exchanger performance will contribute to the higher cost of energy consumption and also utilities to decrease the temperature of products and also to increase the temperature of crude oil.

It is recommended that the analysis of the fouling should be done by considering the other factors too such as the type of crude use, the types of the heat exchanger and etc. The detail consideration of other factor will produced more accurate analysis. It is also recommended that the result of heat transfer characteristic is interpreted in term of economical perspective. The low temperature of crude outlet from the last heat exchanger in preheat train will lead to high cost of energy to increase the temperature to the required value before the crude is fed into the distillation column. This study will be more effective if the impact of fouling is shown in term of economic penalties.

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APPENDICES

A. Example of Fouled Heat Exchanger

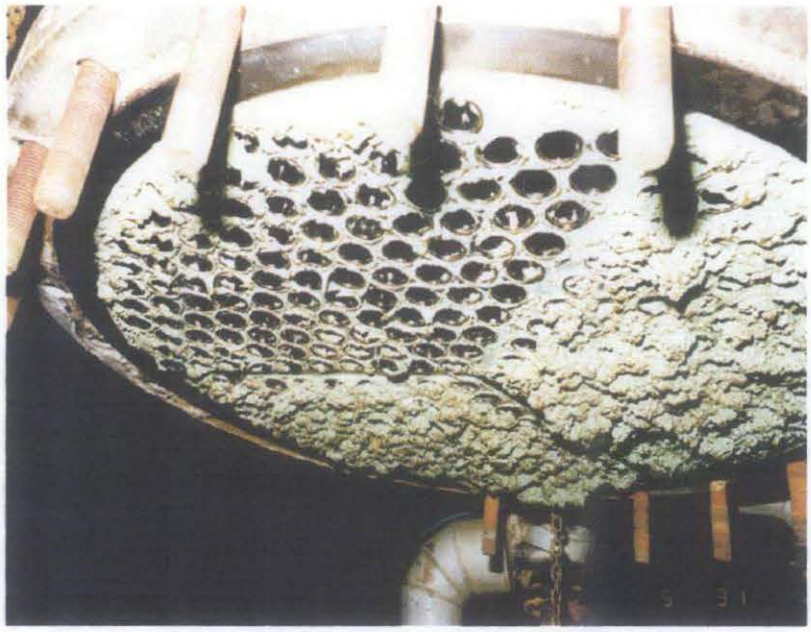
B. Example of Heat Exchanger Datasheet

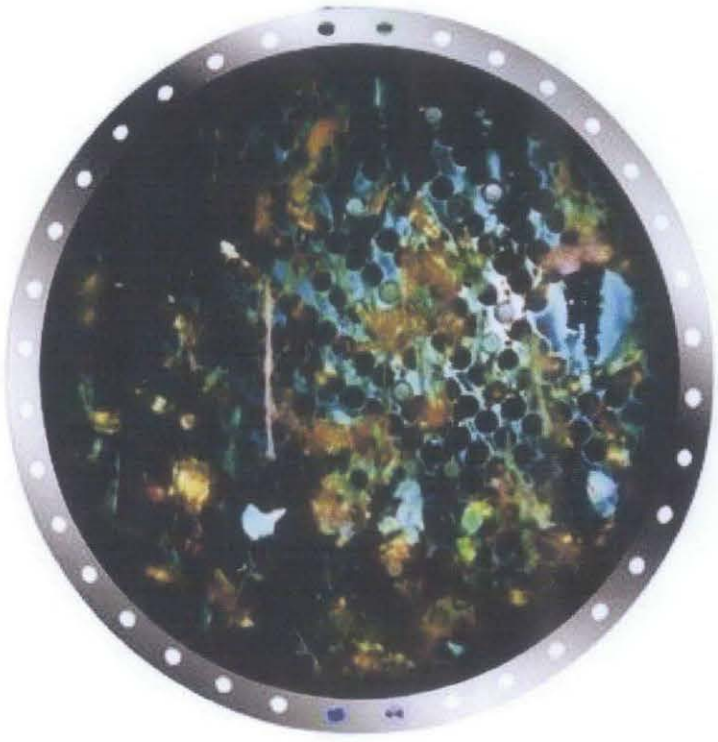
C. Example of Crude Assay Datasheet (Murban)

D. Process Flow Diagram of Crude Preheat Train

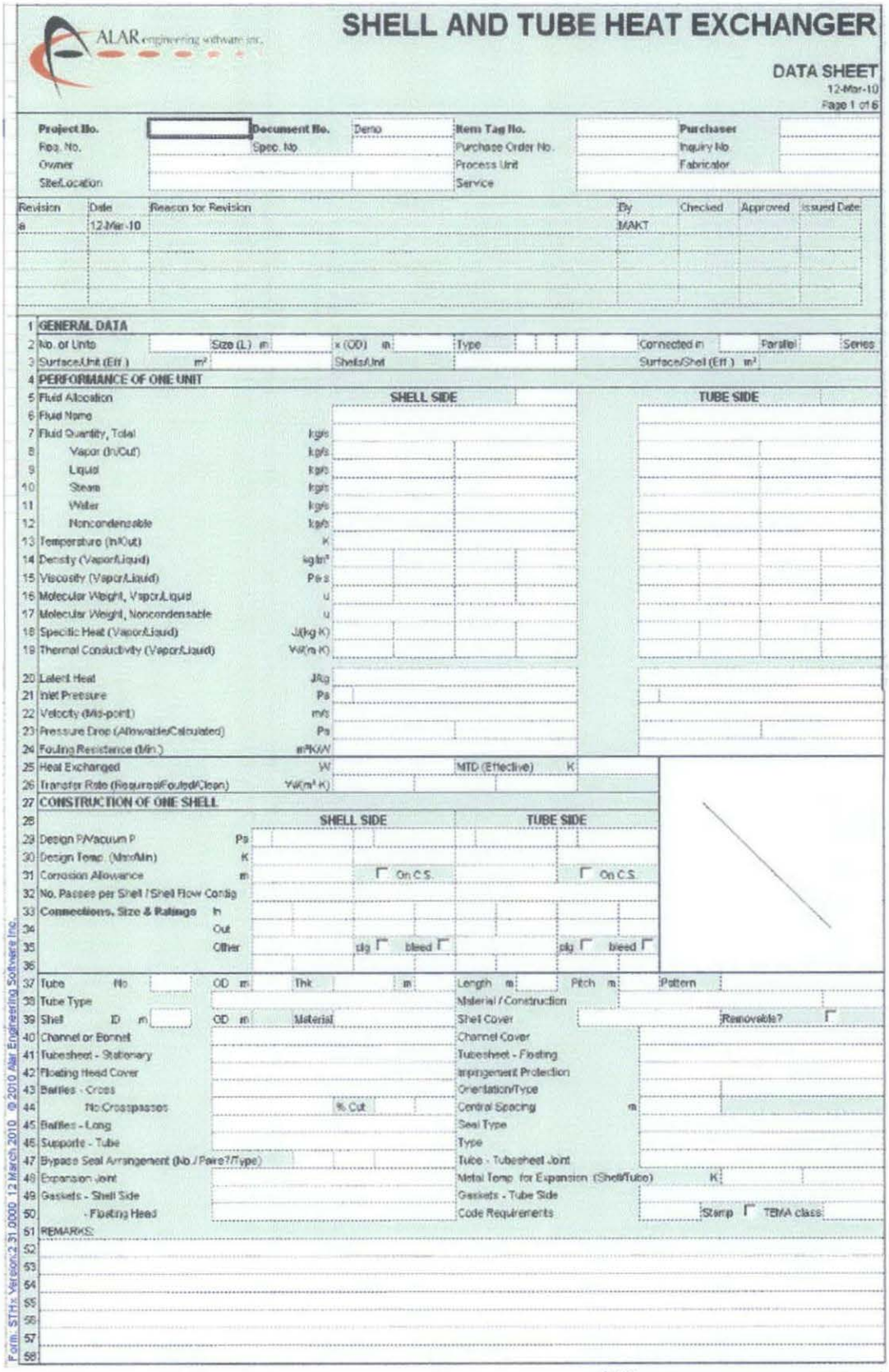
E. Process Design of all Heat Exchangers

APPENDIX A: Example of Fouled Heat Exchanger





APPENDIX B: Example of Heat Exchanger Datasheet



SHELL AND TUBE HEAT EXCHANGER

ALAR engineering software inc.

DATA SHEET

12-Mar-10

Page 1 of 6

Project No.		**Document No.**	Demo	**Item Tag No.**		**Purchaser**	
Req. No.		Spec. No		Purchase Order No.		Inquiry No	
Owner				Process Unit		Fabricator	
Site/Location				Service			

Revision	Date	Reason for Revision	By	Checked	Approved	Issued Date
8	12-Mar-10		MAKT			

GENERAL DATA

No. or Units | Size (L) in | x (OD) in | Type | Connected in | Parallel | Series

Surface/Unit (Eff.) m² | Shells/Unit | Surface/Shell (Eff.) m²

PERFORMANCE OF ONE UNIT

Fluid Allocation		SHELL SIDE	TUBE SIDE
Fluid Name			
Fluid Quantity, Total	kg/s		
Vapor (In/Out)	kg/s		
Liquid	kg/s		
Steam	kg/s		
Water	kg/s		
Noncondensable	kg/s		
Temperature (In/Out)	K		
Density (Vapor/Liquid)	kg/m³		
Viscosity (Vapor/Liquid)	Pa·s		
Molecular Weight, Vapor/Liquid	u		
Molecular Weight, Noncondensable	u		
Specific Heat (Vapor/Liquid)	J/(kg K)		
Thermal Conductivity (Vapor/Liquid)	W/(m K)		
Latent Heat	J/kg		
Inlet Pressure	Pa		
Velocity (Mid-point)	m/s		
Pressure Drop (Allowable/Calculated)	Pa		
Fouling Resistance (Min.)	m²K/W		

Heat Exchanged W | MTD (Effective) K

Transfer Rate (Required/Fouled/Clean) W/(m² K)

CONSTRUCTION OF ONE SHELL

		SHELL SIDE	TUBE SIDE
Design P/Vacuum P	Pa		
Design Temp. (Max/Min)	K		
Corrosion Allowance	m	☐ On C.S.	☐ On C.S.
No. Passes per Shell / Shell Flow Config			
Connections, Size & Ratings	In		
	Out		
	Other	sig ☐ bleed ☐	sig ☐ bleed ☐

Tube No | OD m | Thk m | Length m | Pitch m | Pattern

Tube Type | Material / Construction

Shell ID m | OD m | Material | Shell Cover | Removable? ☐

Channel or Bonnet | Channel Cover

Tubesheet - Stationary | Tubesheet - Floating

Floating Head Cover | Impingement Protection

Baffles - Cross | Orientation/Type

No.Crosspasses | % Cut | Central Spacing m

Baffles - Long | Seal Type

Supports - Tube | Type

Bypass Seal Arrangement (No./Pairs?/Type) | Tube - Tubesheet Joint

Expansion Joint | Metal Temp. for Expansion (Shell/Tube) K

Gaskets - Shell Side | Gaskets - Tube Side

Floating Head | Code Requirements | Stamp ☐ TEMA class

REMARKS:

**(Open source procurement)*

APPENDIX C: Example of Crude Assay Datasheet (Murban)

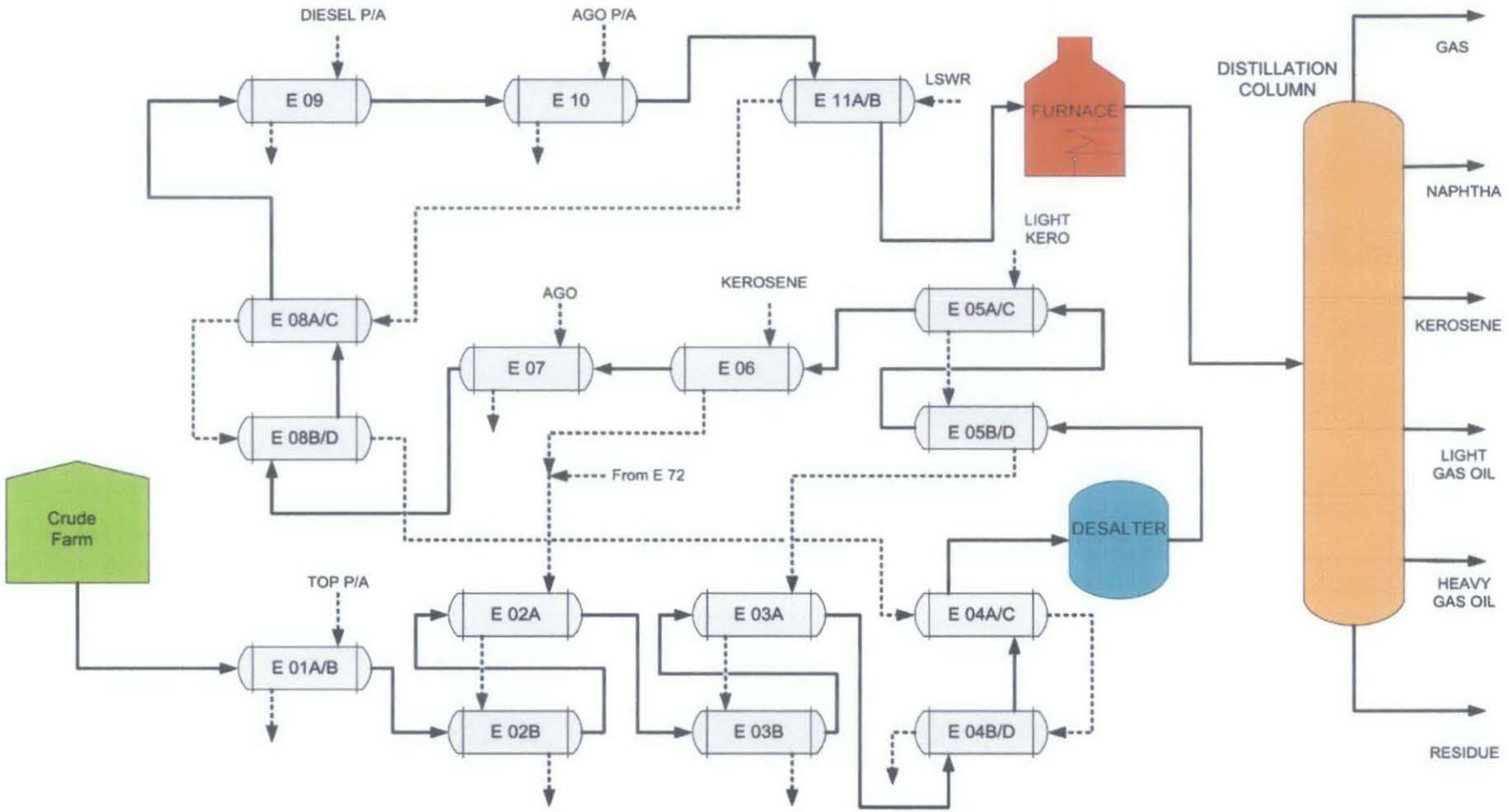
SOURCE OF SAMPLE		CRUDE DATA		ASSAY SUMMARY/TBP DATA		
Reference	AO6995	Gravity	39.3	Yield on Crude	%wt	%vol
		Light Hydrocarbon Analysis		Gas to C4 (corrected)	1.45	1.65
				Light Distillate to 149 C (API)	19.2	22.35
				Kerosine 149 - 232 C	17.35	18.2
Field	ASAB, BAB, BU HASA, ETC, GAHIL, SHAH	Methane %wt	-	Gas oil 232 - 342 C	21.7	21.45
		Ethane %wt	0.01	Residue above 342 C	40.3	36.15
		Propane %wt	0.21			
Export Terminal	JEBEL DHANA	Isobutane %wt	0.25	Gas to C4 (corrected)	1.45	1.65
		n-Butane %wt	0.98			
				Total to 95 C (API)	10.1	12.5
Source	SAMPLE RECEIVED FROM SRC.	Total C1 - C4	1.45	149 C	20.65	24.2
				175 C	26.5	30.5
				232 C	38.0	42.4
				342 C	59.7	63.85
		Isopentane %wt	1.11	369 C	64.75	68.6
Sample Date	25-Jul-95	n-Pentane %wt	1.72	509 C	84.8	87.05
				550 C	89.95	90.75
Date Rec'd	01-Sep-95			Volume expansion of 0.25 per cent vol on crude subtracted from the gas yield		

			DISTILLATES							
TBP cut point C API		Total Crude	C5-95	95-175	C5-149	149-232	232-342	342-369	369-509	509-550
Yield on crude	%wt	100.0	8.65	16.4	19.2	17.35	21.7	5.05	20.05	4.15
Yield on crude	%vol	100.0	10.65	18.0	22.35	18.2	21.45	4.75	18.45	3.7
Density at 15 C	kg/litre	0.8280	0.6740	0.7549	0.7108	0.7888	0.8379	0.8763	0.9999	0.9315
Sulphur	%wt	0.80	0.004	0.017	0.008	0.05	0.39	1.60	1.38	1.71
Mercaptan sulphur	%wt	-	0.0054	0.0062	0.0057	0.0049	-	-	-	-
Viscosity at 20 C	cSt	5.47	-	-	-	-	-	-	-	-
30 C		4.08	-	-	-	-	-	-	-	-
40 C		3.16	-	-	-	1.05	-	-	-	-
50 C		-	-	-	-	-	2.69	6.46	-	-
60 C		-	-	-	-	0.84	-	-	15.99	84.1
100 C		-	-	-	-	-	1.29	2.38	5.59	18.37
Cloud point	C	-	-	-	-	-	-11	14	-	-
Pour point	C	-6	-	-	-	-	-12	12	36	-
Wax	%wt	-	-	-	-	-	3.8	19.5	18	18.1
Total nitrogen	ppm wt	-	-	-	-	-	15	260	660	1200
Basic nitrogen	ppm wt	-	-	-	-	-	-	-	175	520
Organic oxygen	%wt	-	-	-	-	-	-	-	0.1	-
Acidity	mgKOH/g	0.06	-	-	-	0.017	0.03	0.04	0.06	0.06
Carbon residue	%wt	1.7 (C)	-	-	-	-	-	-	0.02	1.3
Asphaltenes	%wt	0.28(C)	-	-	-	-	-	-	-	-
Vanadium	ppm wt	7	-	-	-	-	-	-	-	-
Nickel	ppm wt	4	-	-	-	-	-	-	-	-
Arsenic	ppb wt	-	-	-	-	-	-	-	-	-
Cadmium	ppb wt	-	-	-	-	-	-	-	-	-
Copper	ppb wt	-	-	-	-	-	-	-	-	-
Lead	ppb wt	-	-	-	-	-	-	-	-	-
Mercury (Indication only)	ppb wt	-	-	-	-	-	-	-	-	-
Aromatics	%vol	-	-	-	-	20.2	21.6*	-	-	-
Smoke point	mm	-	-	-	-	24	19	-	-	-
Freezing point	C	-	-	-	-	-56	-8	-	-	-
Aniline point	C	-	-	-	-	56.0	71.9	79.0	90.4	98.1
Cetane Index ASTM D976/IP380		-	-	-	-	43.2/46.1	53.5/54.1	49.9/ -	-	-
Refractive index at 70 C		-	-	-	-	-	-	1.4697	1.4916	1.5014
Hydrogen content	%wt	-	-	-	-	14.0	-	*232 - 342 Aromatics		
Paraffins	%wt	-	84.9	59.2	71.5	-	-		%wt /%vol	
Naphthenes	%wt	-	12.5	21.7	18.1	-	-	1 ring	13.3/14.2	
Aromatics	%wt	-	2.6	19.1	10.3	-	24.7*	2 ring	8.0/ 6.5	
n-Paraffins	%wt	-	45.3	28.9	37.1	-	-	3 ring	1.4/ 0.9	
Colour stability		-	-	-	-	Stable	Stable	369 - 509 DWO		
Naphthalenes	%vol	-	-	-	-	0.52	8.07	Density at 15C	kg/l	0.9191
								Viscosity at 40C	cSt	47.
Salt	lb/1000bbl	< 1	-	-	-	-	-	60C	cSt	19.94
Water	%vol	< 0.05	-	-	-	-	-	100C	cSt	6.23
								Viscosity index		70
Research Octane Number		-	-	-	-	-	-	Pour point	C	-18

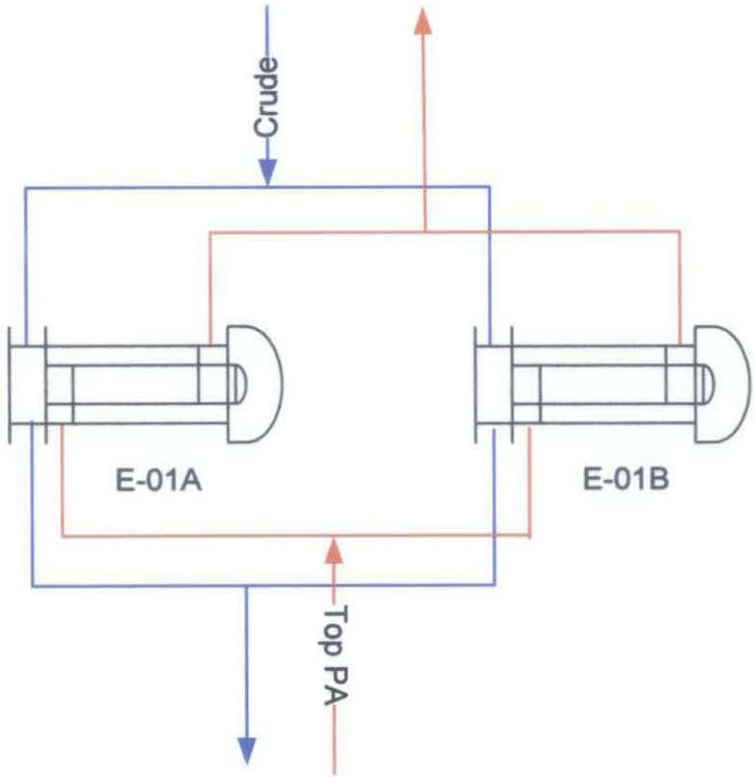
**Based on BP Database (Open source procurement)*

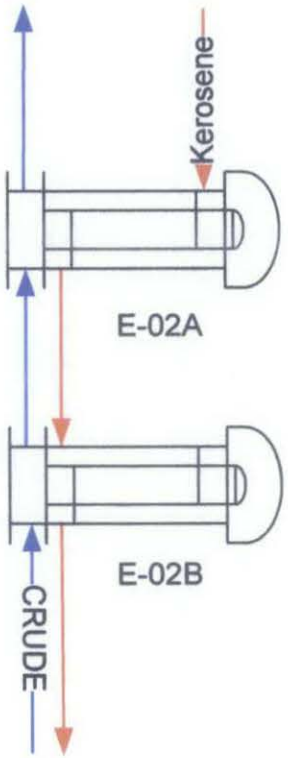
APPENDIX D

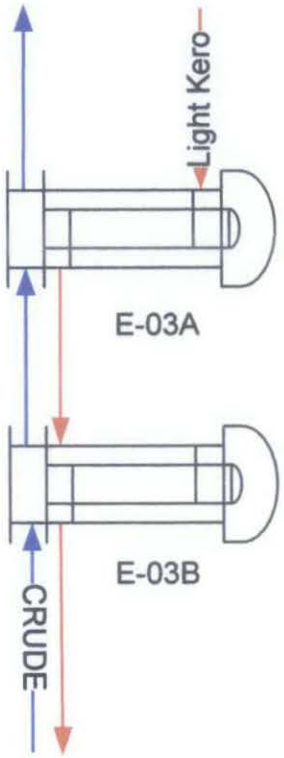
PROCESS FLOW DIAGRAM OF CRUDE PREHEAT TRAIN



APPENDIX E : Process Design of all Heat Exchangers







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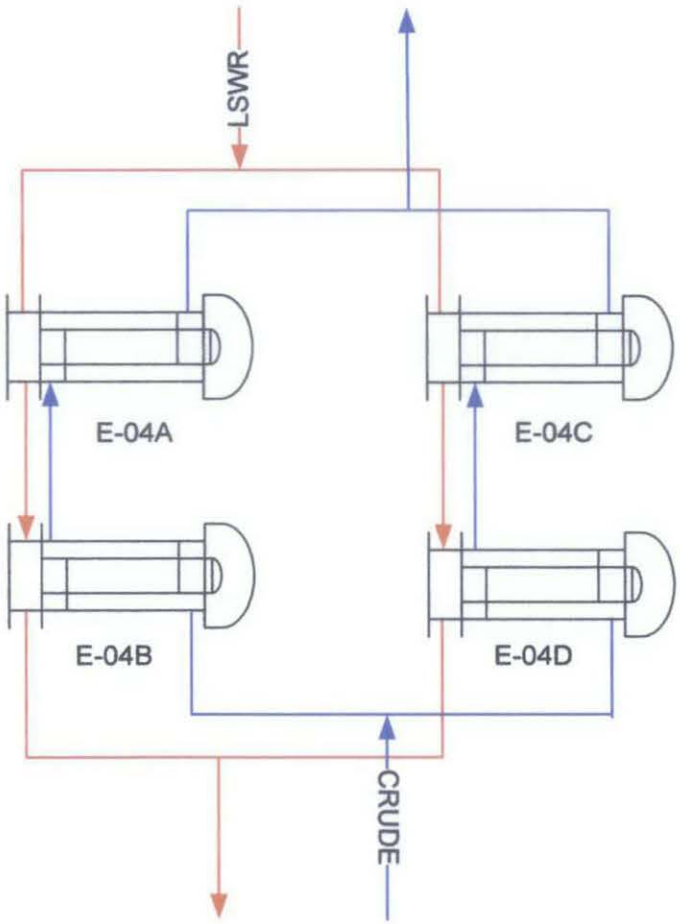

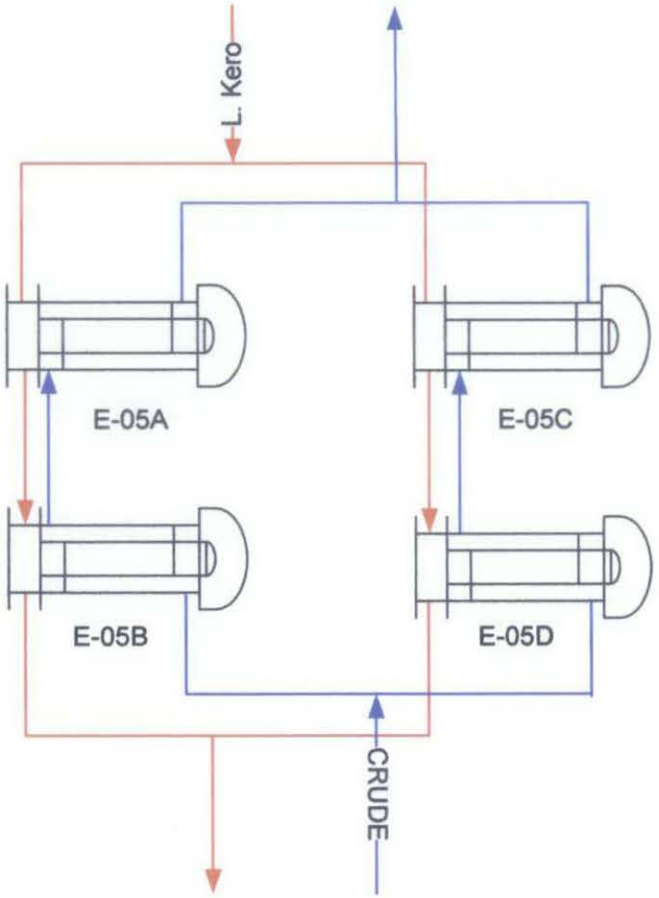

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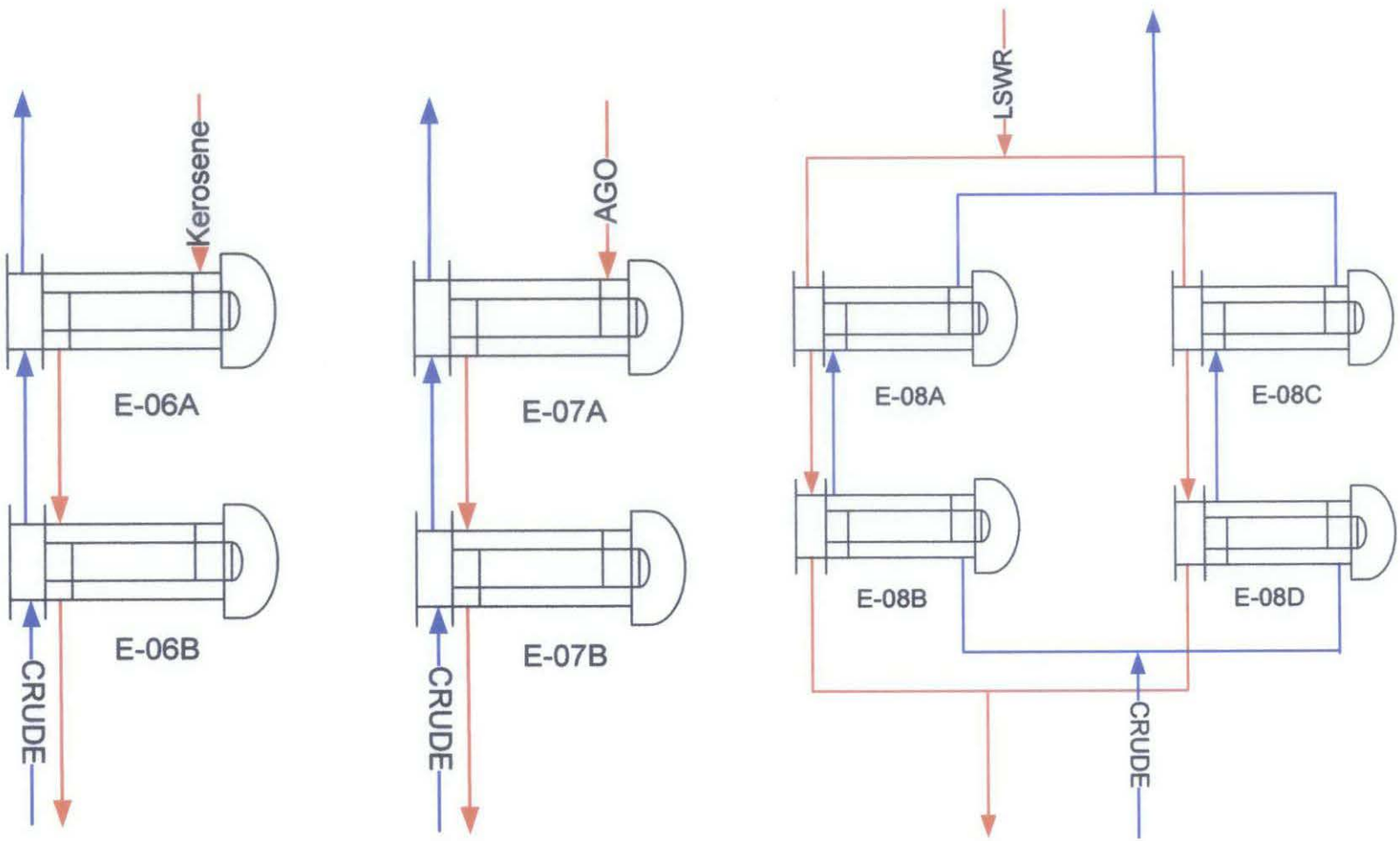

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